Overview of Fermilab “SiteFiller” and LEP3

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Snowmass Agorà on e+e- circular colliders
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Following the discovery of the Higgs at LHC, there has been a renewed interest for a Higgs factory, in particular e^+e^- colliders.
In 2012 Fermilab hosted a workshop on Accelerators for a Higgs Factory (HF2012) with 35 contributions by scientists from Asia, Europe, Russia and US.

e^+e^- collider rings

Dreaming big...

- DLEP: a 50 km e^+e^- would allow doubling the current for the same SR power
- TLEP: a 80 km e^+e^- would allow 3 times larger current for the same SR power
- SuperTRISTAN (40 or 60 km)
- VLLC in the 233 km VLHC tunnel, the larger ancestor of FCC.

Dreaming "small"...

- Fermilab 16 km "SiteFiller"
- LEP3

The need for a Higgs factory is widely recognized by the community.

Luminosity in circular colliders (head-on):

particles/bunch

$$\mathcal{L} = \frac{1}{4\pi}\frac{N^2}{\sigma_x^*\sigma_y^*} n_b f_{rev} R_{hg} \leftarrow \text{Hourglass}$$

Beam-beam tune shift:

$$\chi_z = \frac{r_e}{2\pi\gamma}\frac{N}{(\sigma_x^* + \sigma_y^*)}\sqrt{\frac{\beta_z^*}{\epsilon_z}} = \frac{r_e}{2\pi\gamma}\frac{N}{\sigma_x^*(1+r)}\sqrt{\frac{\beta_z^*}{\epsilon_z}}$$

$r \equiv \sigma_y^*/\sigma_x^*$

$$\mathcal{L} = \frac{\gamma}{2r_e}\frac{\mathcal{I}}{e}(1+r)\frac{\chi_y}{\beta_y^*}R_{hg}$$

At high energy, luminosity in a e^+e^- circular collider is limited by the radiated power

$$W = \frac{e\gamma^4}{3\epsilon_0}\frac{\mathcal{I}}{\rho_b}$$

Luminosity in terms of beam-bean parameter and radiated power per beam (for $r \ll 1$)

$$\mathcal{L} = \frac{3}{2} \frac{\epsilon_0}{e^2 r_e \gamma^3} \frac{\chi_y}{\beta_y^*} \rho_b W R_{hg}$$

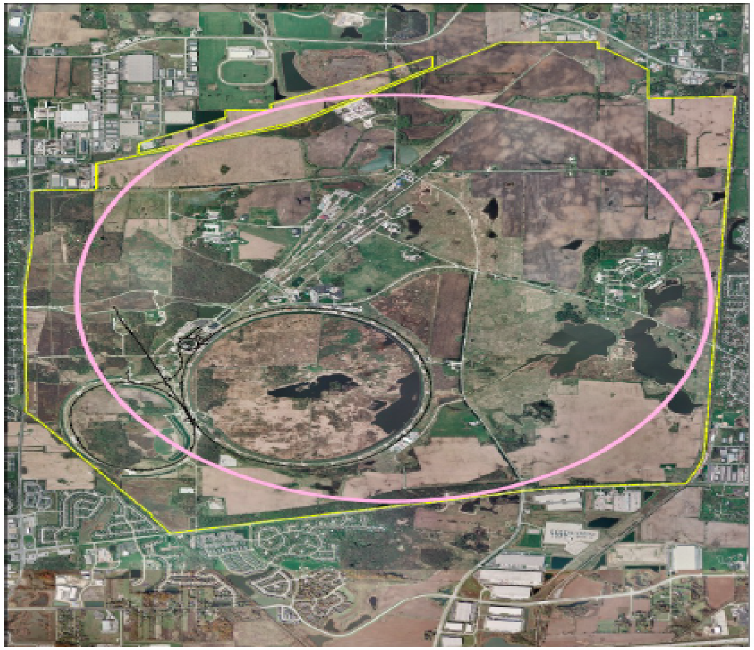
Once the allowed radiated power is fixed $\mathcal{L}$ may be increased only by

- decreasing β_y^*
  - limited by chromaticity budget, magnets aperture...
- going to the beam-beam limit, but
  - single bunch instabilities.
  - lifetime issues for high energy high luminosity e^+e^- colliders
    - Bhabha scattering
    - Beamstrahlung

Lifetime issues call for top-up injection: large average luminosity, but costly.

Fermilab "SiteFiller" Higgs factory

Design strategy for a Higgs factory at Fermilab with a circumference of 16 Km ("SiteFiller"):

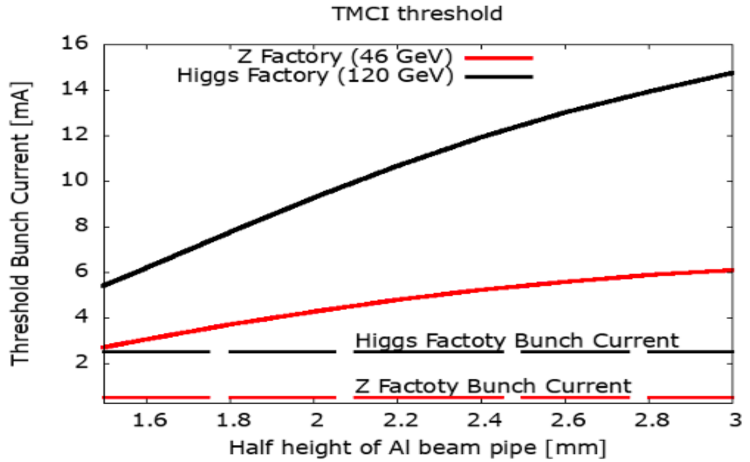


- Total synchrotron radiation power limited at 2×50 MW.
- One IP to
  - maximize bending radius in the arc cells;
  - minimize total beam-beam tune shift;
  - reduce chromaticity.

Tentative parameters:

- $\beta_y^* = 1$ mm.
- 90^0 FODO cells.
- Large number of particles in few bunches.

Single bunch intensity limits.

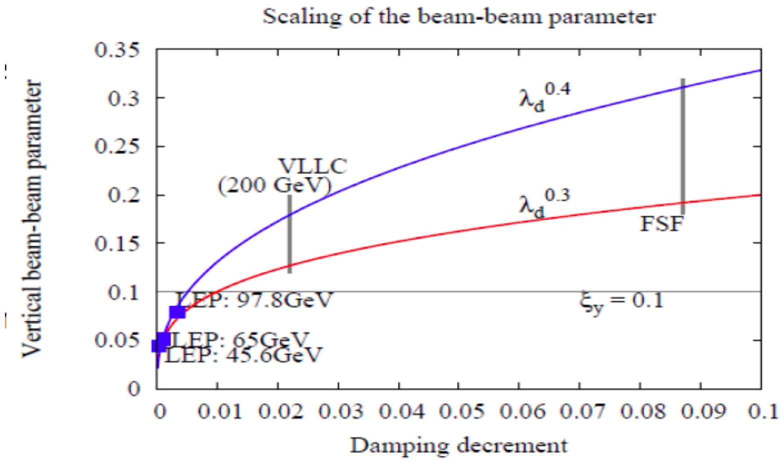


TMCI bunch current threshold

$$\boldsymbol{I_b^{\mathrm{TMCI}} \propto \frac{f_{rev} Q_s E}{e \Sigma_i \beta_i k_{\perp i}(\sigma_\ell)}}$$

Including RF cavities and resistive wall impedance.

Beam-beam interaction parameter $\boldsymbol{\chi}$.



LEP data analysis suggested an increase of the beam-beam limit with energy as

$$\boldsymbol{\chi_y^\infty \propto \lambda_d^a \qquad a = 0.3 - 0.4}$$

with $\boldsymbol{\lambda_d}$ damping time decrement.

Fermilab "SiteFiller" as Z factory

The same ring may be used at 46 GeV for a Z factory. At lower energy when SR is not the limit, we can go to the beam-beam limit. The damping time increment wrt to the Higgs case is $(120/46)^3$ ie τ_ℓ=213 turns. Assuming the "LEP law" the beam-beam limit is ≈0.04.

Luminosity in terms of χ_y with $r \approx 0$

$$\mathcal{L} = \frac{\pi n_b f_{rev}}{r_e^2} (\gamma \chi_y)^2 \sqrt{\frac{\beta_x^*}{\beta_y^{*3}}} \sqrt{\epsilon_x \epsilon_y} R_{hg}$$

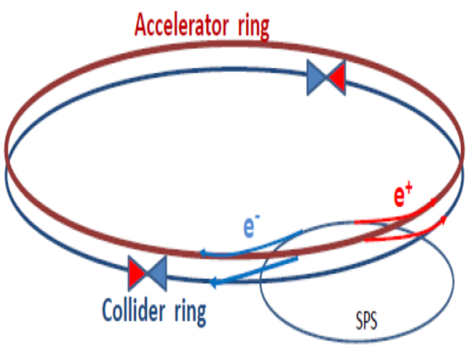
Possible knobs for increasing luminosity:

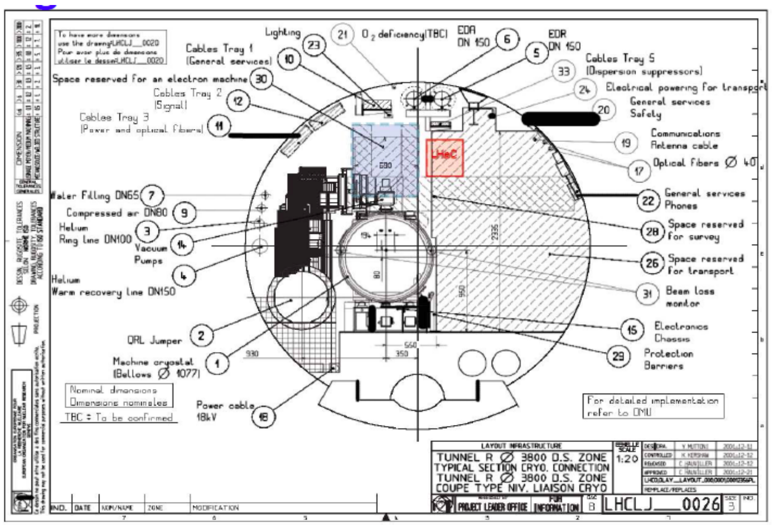
- Increase of horizontal emittance, assuming the IR is unchanged, by
  - introducing wigglers in dispersive regions, but they increase SR, energy spread and bunch length;
  - modifying the phase advance in the arc cells.
- Lowering β_y^*.
- Large number of bunches.
  - Parasitic collisions: crossing angle? pretzel orbits?

LEP3

An e^+e^- single ring collider in the existing LHC (LEP) 26.7 km tunnel.
"Inexpensive" option for the post HL-LHC era if FCC doesn't fly.

- Tunnel exists.
- LHC cryoplants at hand.
- CMS (and ATLAS?) detectors could be (to some extent) reused.
- Cohabitation with LHC (and proposed LHeC): it seemed possible (at performance cost).





It did not receive much support in both 2013 and 2020 ESPPU (source: F. Zimmermann).

Mainly designed as a Higgs factory, could work also as a $\boldsymbol{Z}$ and $\boldsymbol{W}$ factory.

- Total synchrotron radiation power limited by design at 2×50 MW.
  - With a 50% wall-plug to beam efficiency it requires 200 MW.
  - Maximum current $\approx$ 7.2 mA to be distributed in the smallest number of bunches.
- Top-up injection: second ring in the same tunnel possibly on top of the LHC with light-weight magnets.
- 1.3 GHz RF ILC-like for short bunches allows decreasing β^*_y.
- Larger over-voltage wrt LEP to increase momentum RF acceptance.
- 20 MV/m assumed: RF section length about 20% longer wrt LEP2 (104.5 GeV)
  - cryo power about as in LHC.
- Nb_3Sn for IR superconducting quads.
- Arc optics
  - shorter FODO cells allowing lower ϵ_x wrt LEP;
  - small α_p.

Main reference: ATS/Note/2012/062 TECH (LEP3 submission to 2013 ESPPU).

Established technologies, but not yet a mature design. Needed further investigations (similar for the SiteFiller):

- Beam dynamics and large momentum acceptance with 1 mm β_y^*.
- Input power couplers handling 173 kW/cavity RF power in CW.
- HOM heating in presence of large N in short bunches.
- Management of the 100 MW SR (E_c=1.4 MeV).
- Accelerator ring: optics, beam dynamics and operation.

In the meantime some aspects have been revisited. In particular:

- 400 MHz instead of 1.3 GHz.
- Large angle crossing with crab waist scheme.
- Impossibility of hosting all rings in the existing tunnel keeping LHC in place and...
  - even 2 machines in the 3.8 m diameter tunnel are currently questioned.

	LEP3 (ATS Note)	SiteFiller	FCCee (CDR 2018)
Circumference [km]	26.7	16	98
Beam current [mA]	7.2	5.	29
N $[10^{11}]$	10	8.3	1.8
n_b	4	2	328
#IPs	2	1	2
β_x^* [m]	0.2	0.2	0.3
β_y^* [mm]	1	1	1
ϵ_x [nm]	25	21	0.63
ϵ_y [nm]	0.1	0.05	0.001
σ_ℓ [mm] (SR)	2.3	2.9	3.2
b-b tune shift/IP	0.09/0.08	0.075/0.11	0.012/0.12
RF frequency [MHz]	1300	650	400
RF voltage [GV]	12	12	2
η [%]	$\pm$4 (RF)	$\pm$3 (RF)	$\pm$1.7 (DA)
τ_{bs}[min]	>17 (*)	9 (**), 36 (***)	18
τ_{Bhabha}[min]	18	8.7	38
$\mathcal{L}$/IP $[10^{34}$ cm^{-2}s^{-1}]	1.1 (****)	1.0 (****)	8.5

(*) from HF2012 Zanetti simulations with η=$\pm$4%. (**) Using A. Bogomyagkov et al. Eq.19 with η=$\pm$3%.
(***) Zanetti simulations with η=$\pm$3%. (****) Head-on, hourglass included.

	LEP3	SiteFiller
Time between collisions [μs]	22	26
Beam energy range [GeV]	45-120	45-120
Stored energy/beam [MJ]		0.03
Total lost power (both beam)[MW]	100	100
Electrical consumption (total)		1500 GW/h per year
Lenght of accelerators [km]	2×26.7	$2\times 16 \times +16=48$ (*)
Length of all tunnels [km]	27	16
Length of new tunnels [km]	0	16
# of magnets		4488
# of cavities		375 (**)
costs (***)	$\gtrsim$ 3 Billions CHF	$\approx$ 5 Billions USD (****)
Timeline		
time to CDR [years]		3
Time to TDR [years]		5
Construction time [years]	7-10, starting after 2042	7

(*) Assuming 2 booster rings. (**) RF cavities must be distributed. (***) Careful by comparing European and US estimates from different sources! (****) Very preliminary, based on scaling rules!

(Personal) Conclusions

SiteFiller luminosity may be improved by

- lowering emittance arc cells;
- pushing beam-beam tune shift.

However

- Having fixed the ring size for purely contingent reasons limits the SF performance and set additional challenges as:
  - large emittance;
  - large photon critical energy: $\approx$ 2 MeV at 120 GeV;
  - high SR load: $\approx$ 15 kW/m for both beams at 120 GeV;
  - large sawtooth effect.
- The need for infrastructures not at hand at Fermilab (e^+ source, $e^\pm$ injector chain) results in higher costs wrt to the "similar-scale" LEP3.
  - But if LHC tunnel can't host collider and booster, saving is reduced.
  - Timeline may play in favor of the SiteFiller.

For both machine it must be demonstrated that large momentum acceptance and DA (for top-up injection) can be met (in addition to technical challenges).

Acknowledgments

Thanks to

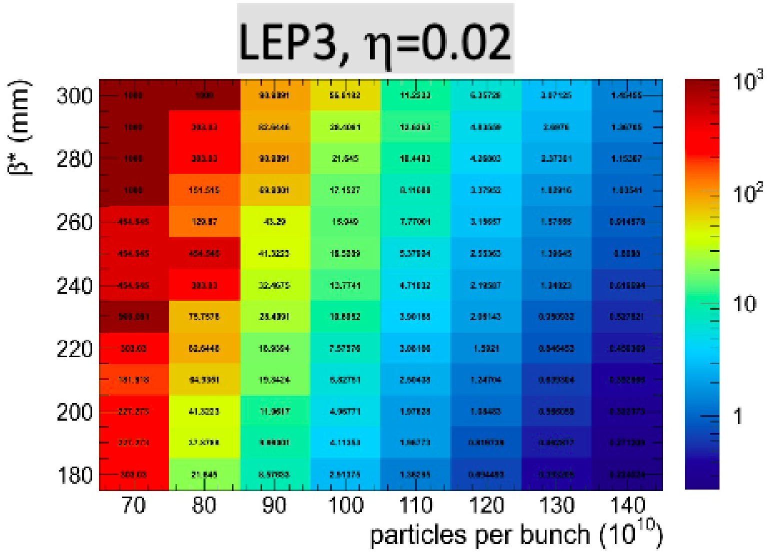
F. Zimmermann for providing LEP3 references and news.

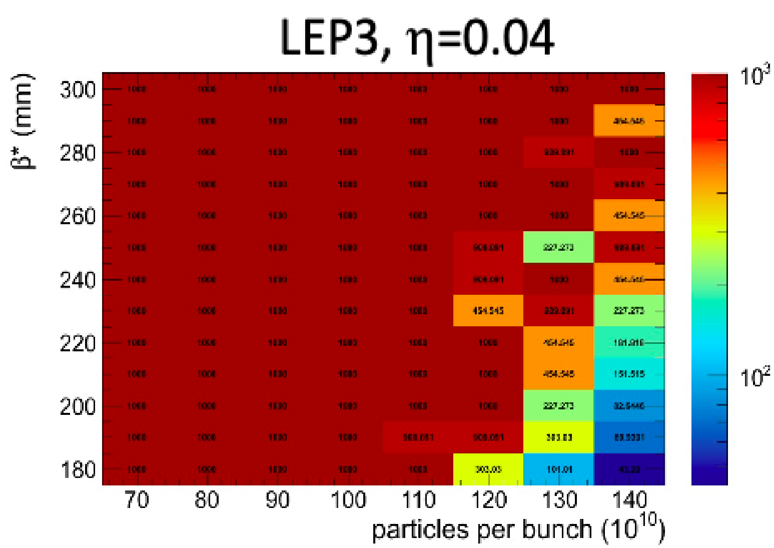
T. Sen for sharing results on his investigations on the SiteFiller.

Back-up slides

Marco Zanetti @ HF2012

- Scan relevant BS parameters:
  - B*x to scale horizontal beam dimension
  - Number of particle per bunch
- BS lifetime for nominal parameters (assuming η=0.04):
  - LEP3: >~ 30 min
  - TLEP-H: ~day
    - >4h for η=0.03, ~4 min for η=0.02





Marco Zanetti (2012) for SiteFiller

$\Delta E/E_{accept}$	Lifetime [sec]
0.01	0.12
0.02	12.0
0.03	2149
0.04	Inf

Higgs e+ e- Collider Parameters

Circumference [km]	16.0
SR power, both beams [MW]	100
Energy [GeV]	120
Hourglass factor	0.695
β_x^*, β_y^* [cm]	20, 0.1
Particles/bunch	$8.3\text{x}\ 10^{11}$
Number of bunches	2
Beam-beam parameters ξ_x, ξ_y	0.077, 0.100
Beam current [mA]	5.
Emittances [nm]	21, 0.05
Energy lost/turn [GeV]	10.0
Rf voltage [GV]	12.1
Damping time (τ_s) [turns]	12
Bremsstrahlung lifetime [mins]	8.7
Luminosity [cm^{-2} sec^{-1}]	$0.99\text{x}\ 10^{34}$

Z factory parameters

	Values
Circumference [km]	16.0
Energy [GeV]	46.0
Luminosity [cm^{-2} sec^{-1}]	6.3×10^{34}
SR power, both beams [MW]	60
β_x*, β_y* [cm]	20, 0.1
Particles/bunch	1.7×10^{11}
Number of bunches	279
Beam-beam parameters ξ_x, ξ_y	0.032, 0.045
Beam current [A]	0.14
Emittances [nm]	26.1, 0.065
Energy lost/turn [MeV]	216
Rf voltage [MV]	241
Damping time (τ_s) [turns]	213
Bremsstrahlung lifetime [hrs]	0.62
Beamstrahlung upsilon parameter	0.29×10^{-4}

T. Sen e+e- ring at Fermilab